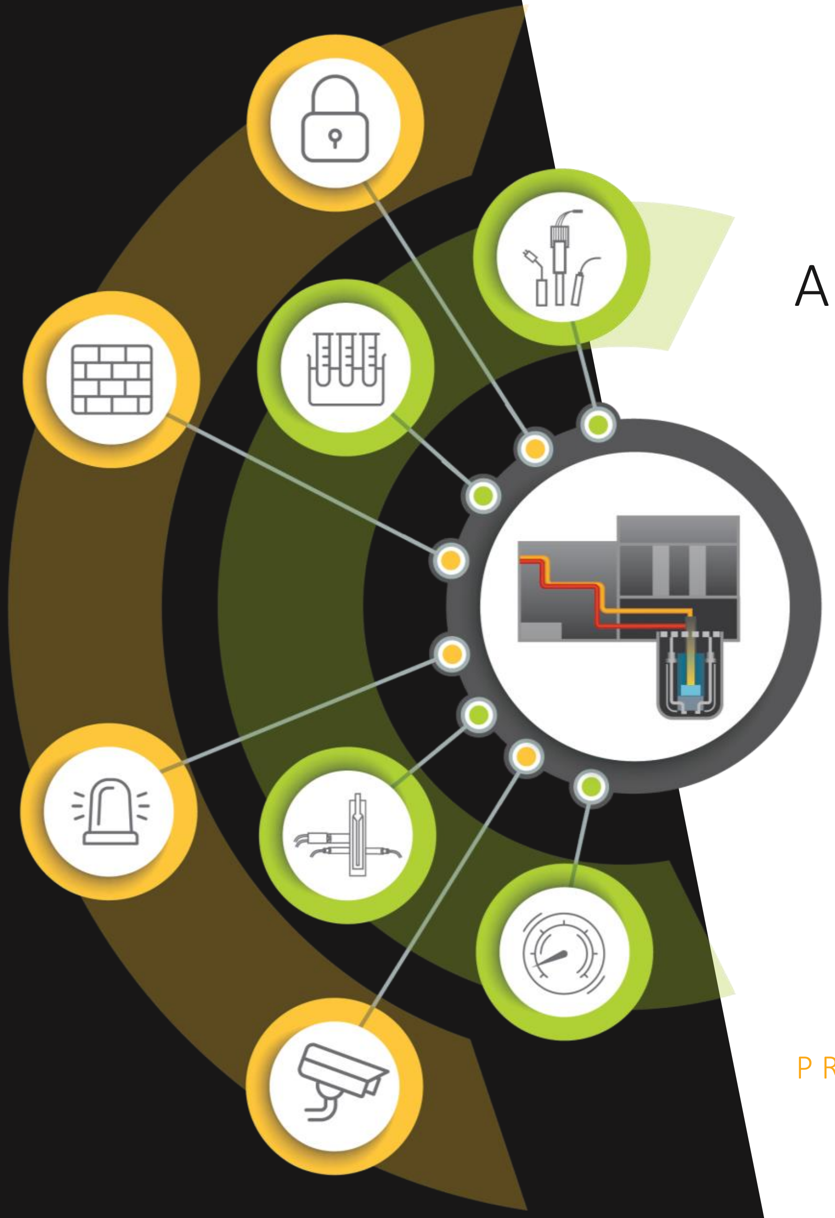

ADVANCED REACTOR SAFEGUARDS

MC&A for Pebble Bed Reactors

April 2023 Program Review

PRESENTED BY

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April 19, 2023

Fiscal Year 2023

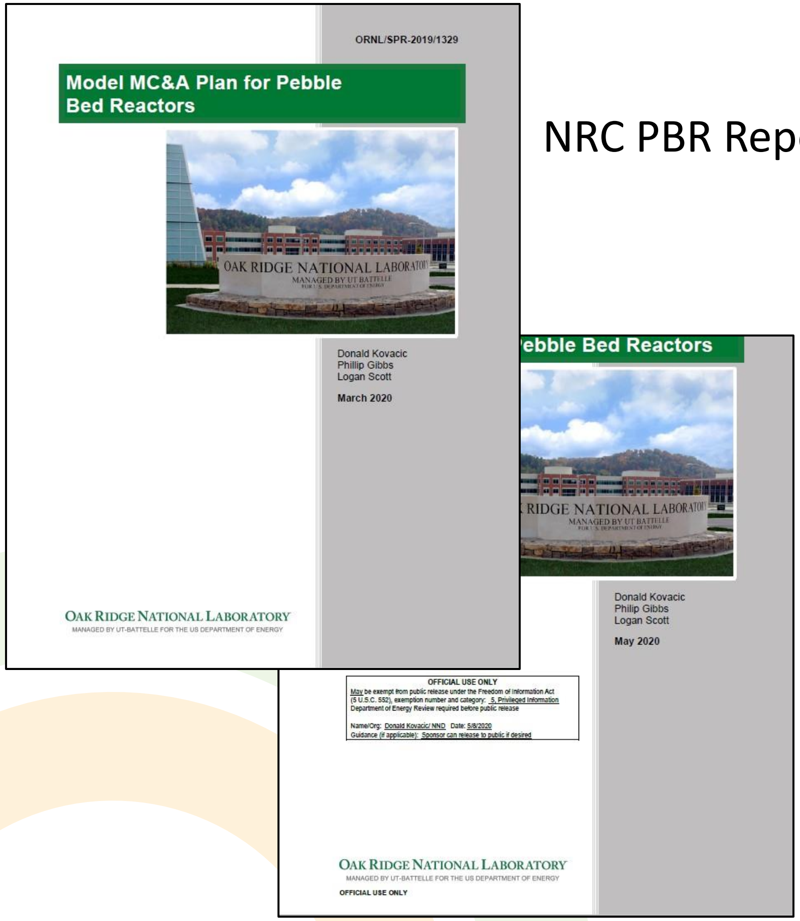
Compile main work done to date on recommended approaches for Pebble Bed Reactor (PBR) Safeguards (M2 Milestone).

- Material control, transfers, shipments/receipts, and Inventory
- Fresh/Spent fuel measurements
- Statistical approaches
- Reporting / Material Control and Accounting System
- Reactor Core Modeling

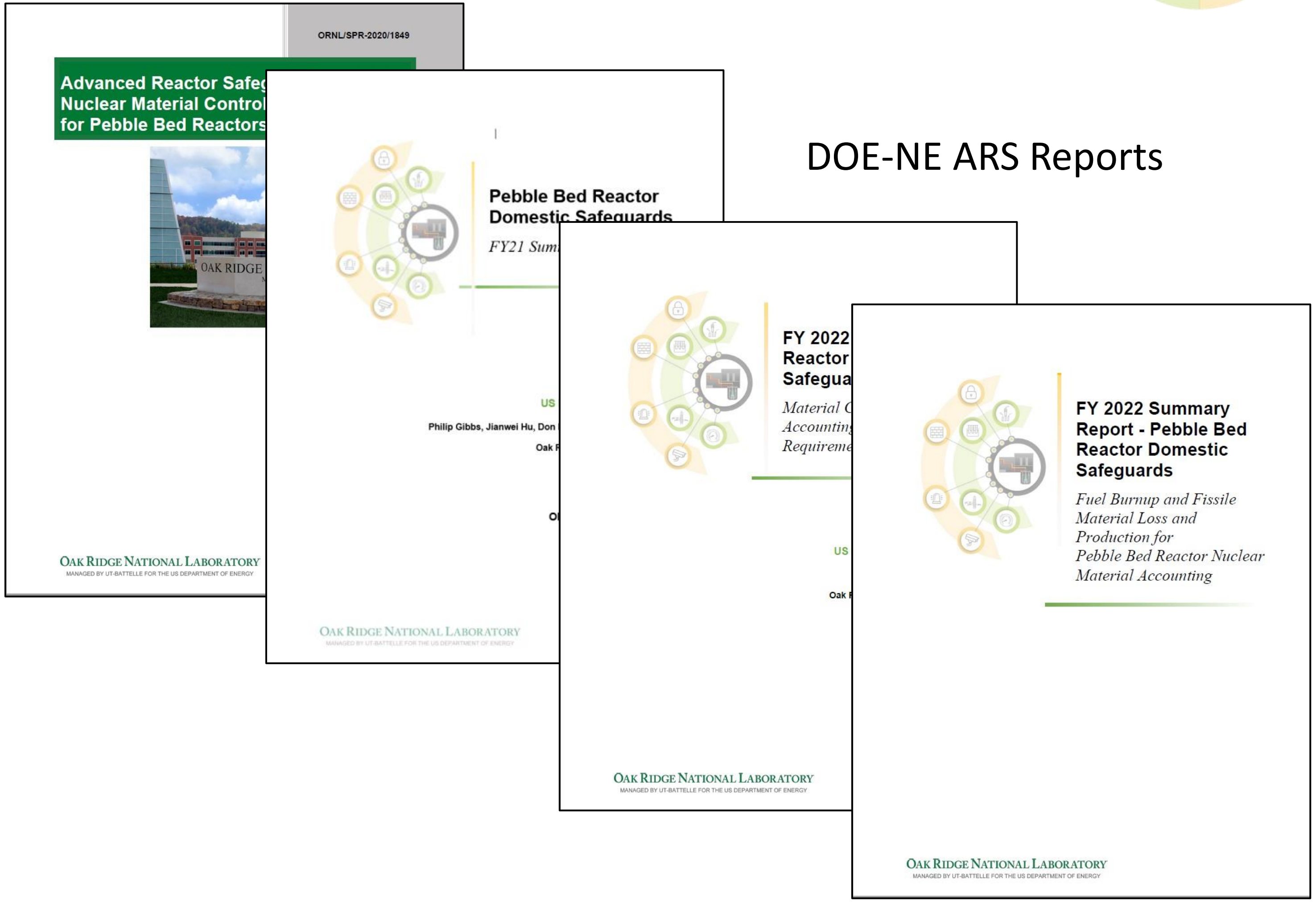
Key theme – MC&A in PBRs is about counting pebbles

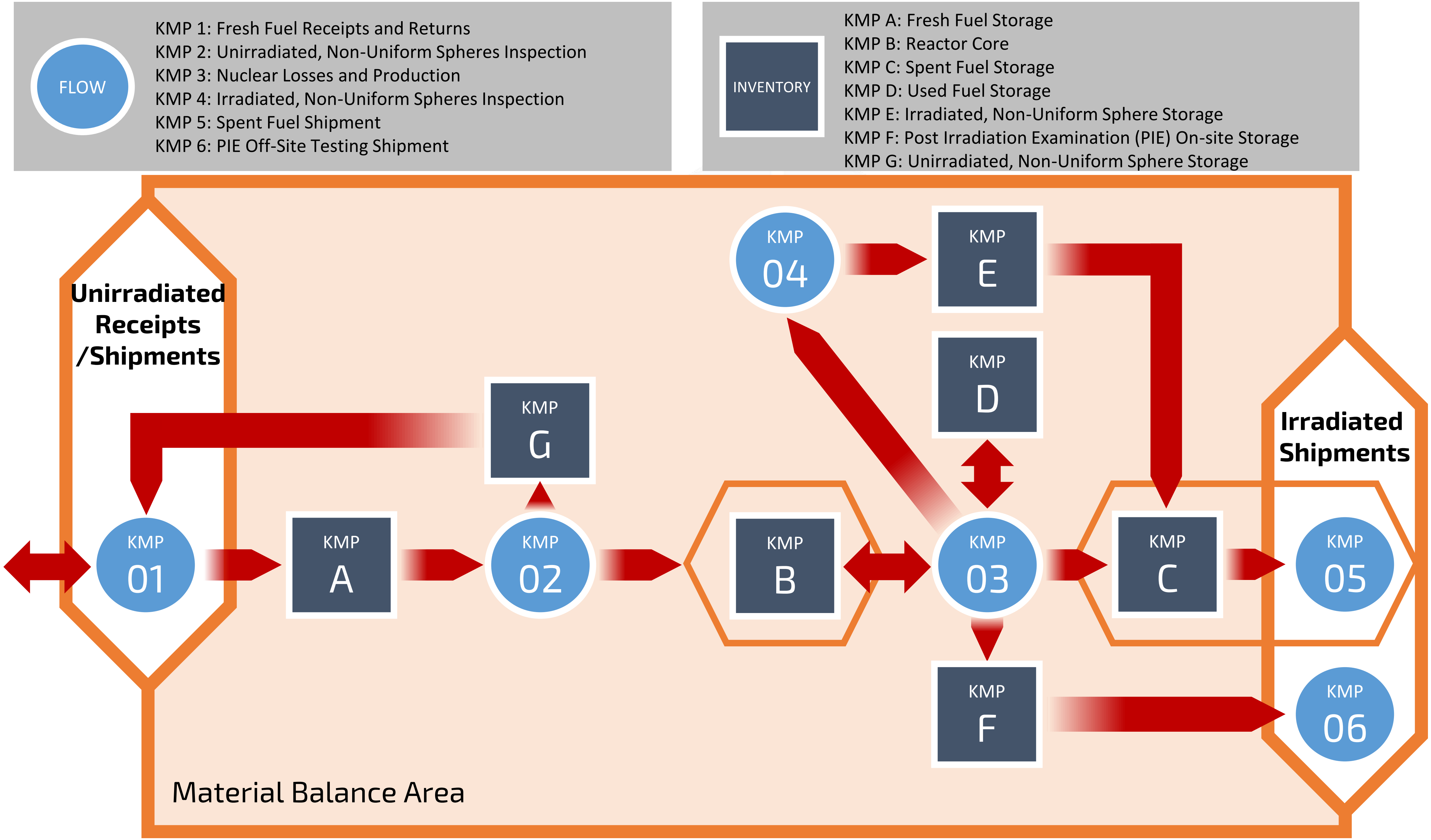
ORNL PBR Related Work – 2019-2022

NRC PBR Reports



DOE-NE ARS Reports




FLOW
KMP 1: Fresh Fuel Receipts and Returns
KMP 2: Unirradiated, Non-Uniform Spheres Inspection
KMP 3: Nuclear Losses and Production
KMP 4: Irradiated, Non-Uniform Spheres Inspection
KMP 5: Spent Fuel Shipment
KMP 6: PIE Off-Site Testing Shipment
INVENTORY
KMP A: Fresh Fuel Storage
KMP B: Reactor Core
KMP C: Spent Fuel Storage
KMP D: Used Fuel Storage
KMP E: Irradiated, Non-Uniform Sphere Storage
KMP F: Post Irradiation Examination (PIE) On-site Storage
KMP G: Unirradiated, Non-Uniform Sphere Storage
Unirradiated Receipts /Shipments
KMP 04
KMP E
KMP D
KMP G
Irradiated Shipments
KMP 01
KMP A
KMP 02
KMP B
KMP 03
KMP C
KMP 05
KMP F
KMP 06
Material Balance Area

SNM Content of a Spent Pebble – FY22 Work

Table 1. Comparison of average isotopic mass (mg) per pebble with previous work.

Nuclide	Initial	Retired pebbles	All pebbles after pass 6 (this work)	All pebbles after pass 6 (previous work [21])
^{234}U	7.690	4.8 ± 0.1	4.8 ± 0.1	N/A
^{235}U	864.00	141.8 ± 19.6	145.5 ± 21.9	185 ± 11
^{236}U	3.974	116.1 ± 2.2	115.6 ± 2.5	N/A
^{238}U	8,124.34	7,755.8 ± 21.1	7,753.1 ± 13.6	7,690 ± 50
Total U	9,000	8,018.4 ± 28.9	8,019.1 ± 25.9	7,875 ± 51.2
^{238}Pu	0	2.3 ± 0.3	2.3 ± 0.3	2.8 ± 0.2
^{239}Pu	0	52.2 ± 6.0	53.6 ± 5.3	57 ± 9
^{240}Pu	0	35.5 ± 1.3	35.7 ± 0.9	30 ± 3
^{241}Pu	0	19.3 ± 1.5	19.7 ± 1.1	28 ± 4
^{242}Pu	0	14.6 ± 1.6	19.4 ± 1.5	20 ± 2
Total Pu	0	123.9 ± 6.5	125.9 ± 4.6	137.8 ± 10.5

Estimate U and Pu inventories in an APR-1400 spent fuel assembly

Isotope	Inventory (kg)
U total	397.2
^{234}U	0.071
^{235}U	2.61
^{236}U	2.44
^{238}U	392.0
Pu total	4.45
^{238}Pu	0.16
^{239}Pu	2.60
^{240}Pu	1.30
^{241}Pu	0.73
^{242}Pu	0.43

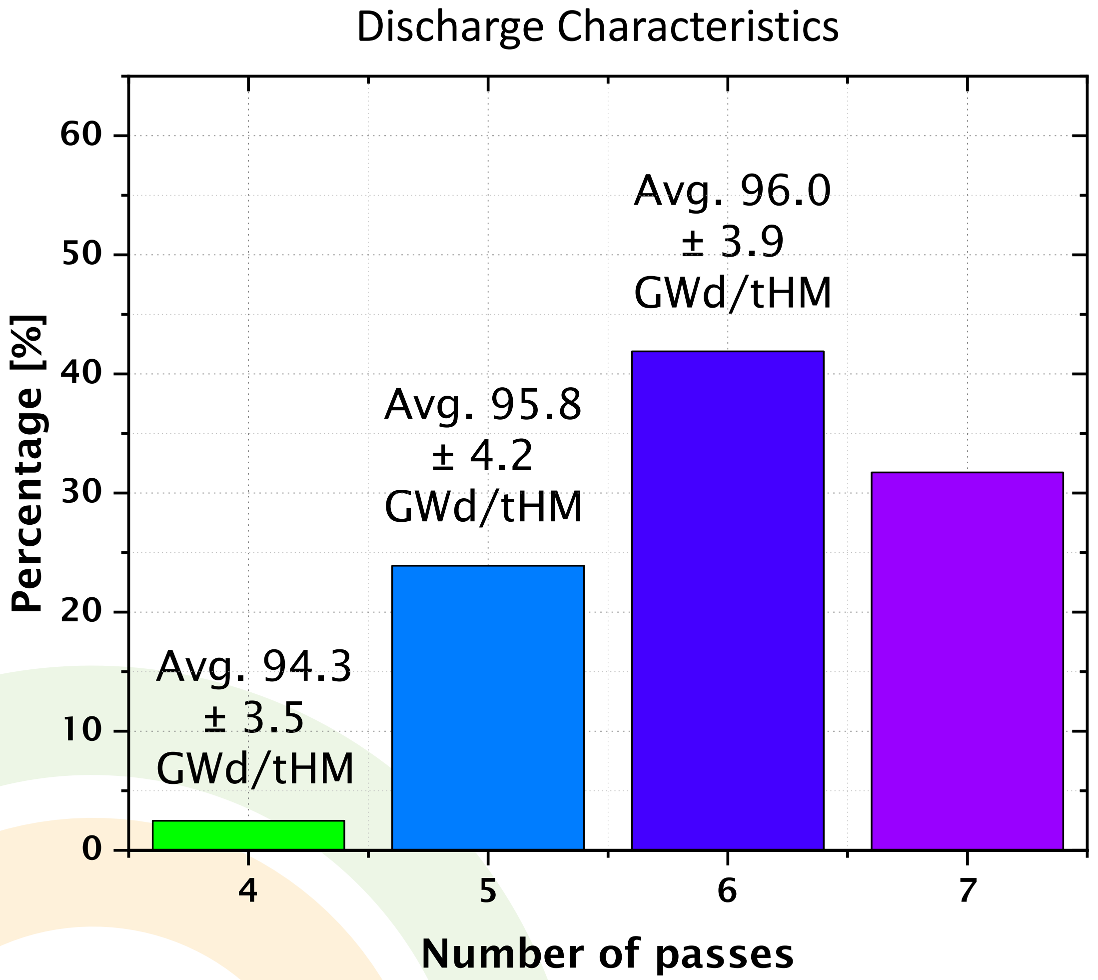
Assuming 2000 pebbles in spent fuel container = 0.276 kg

Statistics for PBRs

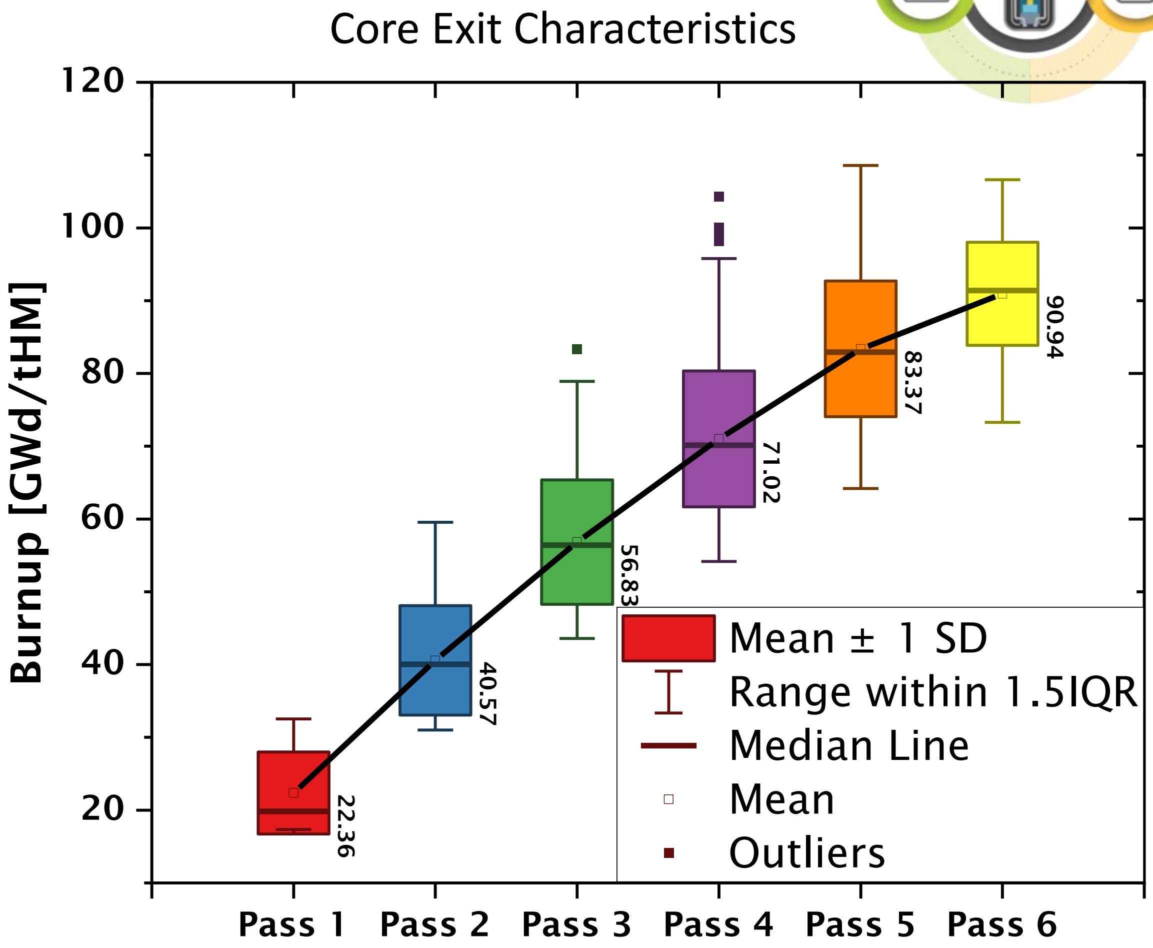
Statistical Decisions for PBRs

1. Burnup measurement discharge decision
2. Burnup measurement versus reactor code comparison
3. Analysis of Variance (ANOVA) between reactors

1 - Burnup Measurement Discharge Decision

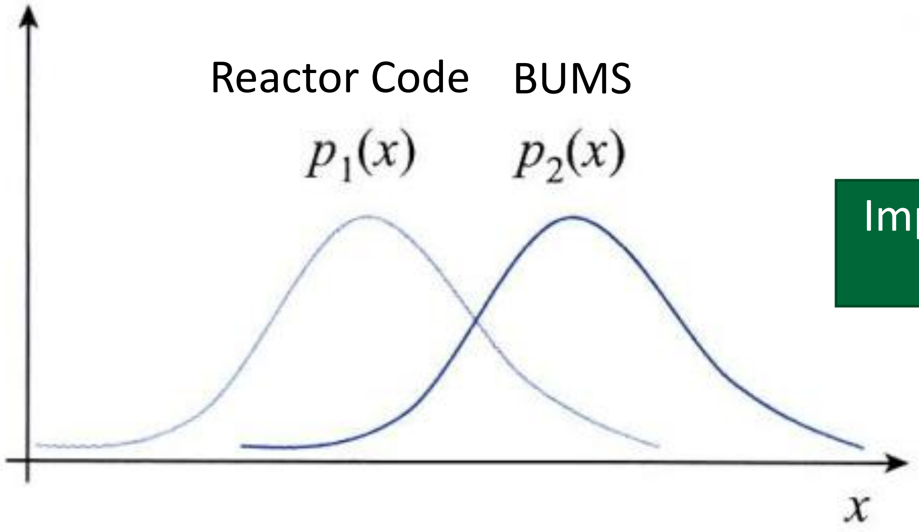


Target discharge burnup is 90 GWd/MTU achieved for about 65% of pebbles in 6 passes.



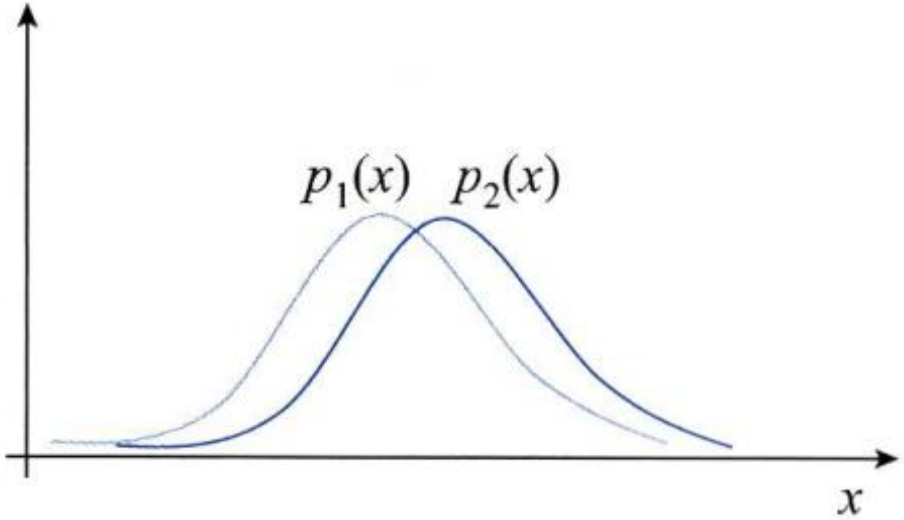
Outliers are those pebbles outside of the 1.5 Inter-Quartile Range (IQR). For a normal distribution, this would be outside approx. +/- 3σ.

2 - Burnup Measurement (BUMS) versus Reactor Code Comparison



First deployments – 2030s

Improvements over time



Fully mature technologies

Note: Some form of sampling along with post irradiation examination would also be valuable

SNM Calculations - Reference

Material Control Systems for Nuclear Power Plants (ANSI N15.8-2009) Section 9.0

- ***Methods of computation*** *shall be established and utilized for determining the total element and isotopic composition of SNM in irradiated nuclear fuel assemblies and fuel components. The computed values are the basis for shipment documents, as required in 10 CFR 74.15, and material status reports, as required in 10 CFR 74.13.*
- ***Refinement of the element and isotopic computations*** *used in determining the SNM content of irradiated fuel should be considered as new technologies evolve. <u>For reprocessed fuel, this may include a collection and comparison of reprocessing plant measurement data with computed data for fuel assemblies.</u>*

Why is this important?

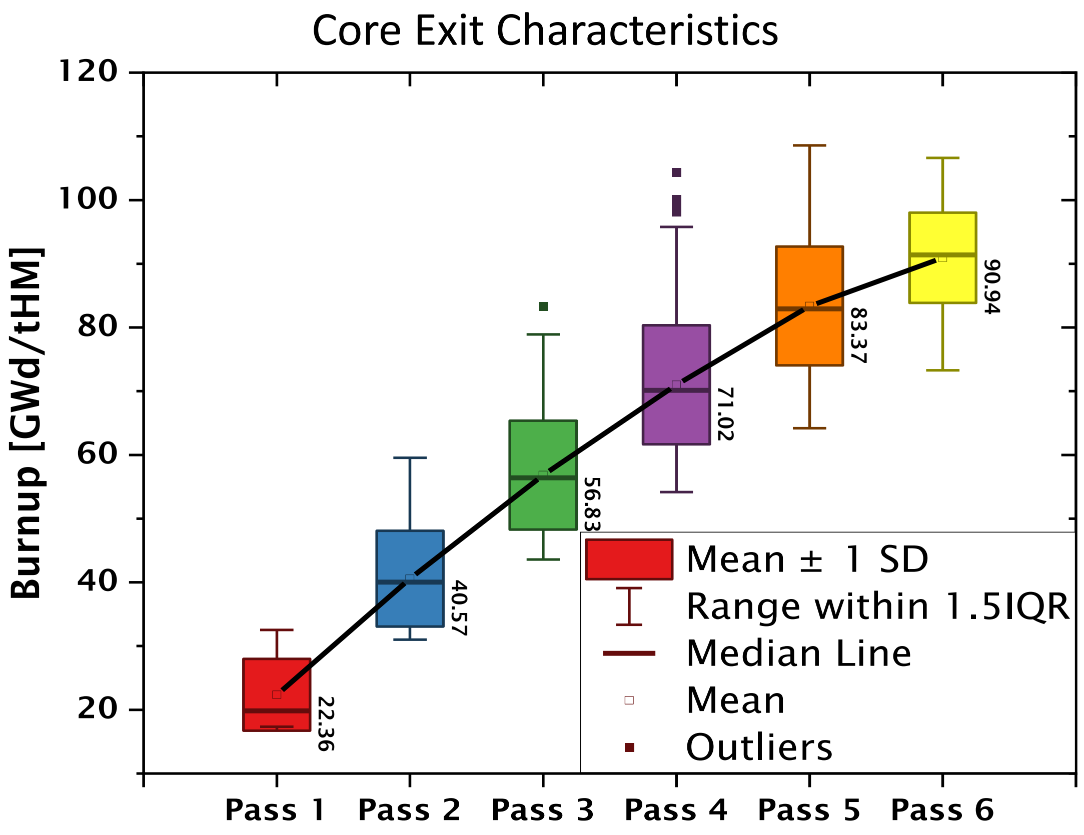
- Around 70% of the U.S. historical inventory difference (or MUF) is due to incorrectly handling this
- Incorrect handling is a significant contributor to shipper/receiver differences if/when fuel is processed

3 - Analysis of Variance – differences between reactors

Analysis of Variance (ANOVA) is a statistical formula used to compare different groups. A range of scenarios use it to determine if there is any difference between the different groups.

For PBRs could be used to:

- Misuse of reactor
- Operational
  - Instrumentation Issues
  - Fuel flow through core
  - Fuel optimization



Discussion – What Next? (seed topics for breakout)

- Present:
- Transition to direct vendor support through ARDP and ARPA-E
- Future:
- Spent fuel canister measurements – 2030 to 2040
  - Adapt current LWR measurement methods to PBR spent fuel canister designs
- Independent post irradiation examination – 2030 to 2040
  - Support sampling and destructive analysis of spent pebbles to inform reactor code and burnup measurement system methods (ORNL/INL/SRNL?)
- PBR Measurement Method target values – 2040 publication of STR-368 on International Target Values
- Develop understanding of fuel performance in commercial operation (*note: includes failure mode analysis as applicable*)
- Additional work on characteristics of flow through core

Summary

- Reviewed work done to date plus discussion on FY23
- Revisited material flows, quantities, and statistical approaches
- Provided a few ideas for future work (10-20 years)

Backup Slides on piece count

Key characteristics of fuel spheres affecting MC&A approach

1. Pebbles are all the same to within milligrams *(e.g., this is a manufactured finish product to specifications that exceed MC&A reportable units which are 1 gram)*
2. SNM content is small per sphere *(e.g., an adversary would have to take a lot)*
3. Stealing or diverting part of the SNM from a pebble isn’t likely credible which factors into IAEA concept of “batch” as applied to this process.
4. The MC&A and security systems will be focused on tracking pebbles not “measured SNM”. The SNM content (*points 1 and 3*) *“goes along for the ride”* at the manufactured value.

Batch versus Item versus Bulk

Batch/Piece Count

- SNM contained in several similar things
  - Spheres
- Groups of similar things tracked in the accounting system as a single unit or group
- Those units or groups are:
  - Shipping Container
  - Spent Fuel Container
  - Reactor Core/Fuel Handling System
  - Other sphere containers

Item

- Smallest subdivision in the accounting system
- Uniquely identified

Bulk

- Typically exist in tanks or processing lines as solution, powders, metal, gas, etc.
- Impossible to distinguish among individual items

Piece count as used by US Department of Energy

"In some cases, it is not desirable to account for each "item" (component) individually." This might be the case if there are a large number of (similar non-uniquely identified) items." LANMAS Users Manual (DOE's standard MC&A system)*

- The DOE approach represents this large number of components with a single identifier (e.g., drum, storage location, Process, etc.) along with a "count" of the number of components represented by that identifier or group.

- The total SNM content in the group is the sum of the SNM in the components which in this case is a fixed value.

* For the purposes of this discussion, component is defined as the fuel sphere

A challenge or nuance with the term Batch as used by the IAEA

IAEA Safeguards Glossary

6.7. Batch – "a portion of nuclear material handled as a unit for accounting purposes at a key measurement point and for which the composition and quantity are defined by a single set of specifications or measurements. The nuclear material may be in ~~bulk form~~ or contained in a number of separate items**"*

*Challenge is making sure the common understanding of "batch" is narrowed as to how it applies to a sphere inventory. A sphere inventory is NOT really a bulk inventory.

** Spheres technically don't meet the definition of an item since they are not uniquely identified. However, with the exception of the unique identification they behave like sealed items or sealed sources.